THE RELATION OF OPEN MAGNETIC STRUCTURES OF SOLAR CORONA TO GEOMAGNETIC DISTURBANCES

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Abstract: In this paper, coronal magnetic field structures are compared with coronal holes, interplanetary plasma and magnetic fields, and geomagnetic disturbances. The comparison is made for four selected periods, two in times of low solar activity and the remaining two in high solar activity. As a result, evidence is given that open magnetic structures are formed in the solar corona during both low and high solar activity periods, and that the open field regions are the sources of corotating high-speed solar wind streams. In particular, it is shown that recurrent series of geomagnetic disturbances are seen regardless of solar activity which are well associated with the central meridian passage of long-lived open field regions. In one case, geomagnetic activity of recurrent disturbances is found to be well correlated with the evolution of the corresponding open field region. This study emphasizes the importance and usefulness of pursuing evolutionary changes in coronal magnetic structures to the study of recurrent geomagnetic disturbances.

1. Introduction

Strong evidence was presented in the declining phase of solar cycle 20, that the sources of corotating high-speed solar wind streams are coronal holes. This result is attributed mainly to synoptic solar maps obtained from a series of spacecraft observations, particularly from the OSO-7 and Skylab experiments, along with those obtained from the ground-based coronal and chromospheric observations (NEUPERT and PIZZO, 1974; BELL and NOCI, 1976; NOLTE *et al.*, 1976; HANSEN *et al.*, 1976; SHEELEY *et al.*, 1976, 1977). More recently, coronal magnetic field structures calculated by spherical harmonic analysis of the measured photospheric magnetic fields were compared with the coronal holes and the interplanetary plasma and magnetic field observations (LEVINE *et al.*, 1977; BURLAGA *et al.*, 1978; LEVINE, 1978). One of the most important findings of these studies is the existence of the regions of open magnetic field lines other than the open field regions associated with coronal holes. The observed solar wind structures are understood better by taking those open magnetic field regions as possible sources of solar wind, in addition to the sources associated with coronal holes. Thus, BURLAGA *et al.* (1978) suggest that open field regions may be more basic than coronal holes as sources of interplanetary plasma and magnetic fields.

The above results offer an improved approach to the identification of the origin of corotating streams causing geomagnetic storms. On the basis of this idea, MARUBASHI and ISHII (1980) made an attempt to identify the causes of individual magnetic storms which had occurred in 1977 and 1978. They found that there are many non-recurrent sporadic storms caused by short-lived corotating streams in the investigated period corresponding to the increasing phase of solar activity in solar cycle 21. This result raises a suspicion that the relation between magnetic storms and the causal solar flares may have been obscured by the existence of such magnetic storms in the early studies (see COOK and MCCUE, 1975, for a review of studies relating storms to solar flares). It is because some of the magnetic storms caused by short-lived corotating streams could have been taken to be caused by solar flares in those studies. Therefore, renewed attempts are desirable to identify the causes of individual magnetic storms with data of longer period so as to cover a full solar cycle. In addition, it is expected that such studies provide an insight into the long-term evolution of corotating streams and also an approach to the study of dynamics of streams in interplanetary space from the stream origin to the earth.

The possibility for such extended studies was presented by the publishing of the Atlas of Magnetic Fields in the Solar Corona by NEWKIRK *et al.* (1973). The Atlas provides maps of both the strong and general coronal magnetic fields computed with the use of the Mt. Wilson magnetograph data for the period from August 1959 to January 1974. The purpose of this paper is to present some results of a study of the relation between open magnetic structures of solar corona and geomagnetic disturbances with the Atlas data for selected periods. We begin by comparing the coronal magnetic field maps from the Atlas with similar maps of higher resolution published in the literature (LEVINE, 1977; BURLAGA *et al.*, 1978) and the interplanetary plasma and magnetic field observations. The comparison aims not only at confirming the importance of open magnetic structures but also at testing the reliability of the Atlas data. Then, the correlations between coronal open magnetic structures and geomagnetic disturbances are examined for the two selected periods: December 1959 to June 1960, and June 1963 to January 1964. These periods were selected because they exhibit apparent recurrence tendency of geomagnetic activity, one in times of high solar activity, another in low solar activity, and the both in solar cycle 19.

2. Comparison between Coronal Magnetic Fields and Interplanetary Streams

The Atlas of Magnetic Fields in the Solar Corona published by NEWKIRK *et al.* (1973) consists of two series of both the general and strong field maps drawn for every 10° of central meridian longitude in the Carrington system. An example of the general field map is shown in Fig. 1a, which gives the appearance of the coronal magnetic structure as viewed from the solar equatorial plane. In this map, a field line is plotted from the center of each of the 24 × 27 surface elements having equal area if projected on the cylinder tangent to the photosphere. By using this type of maps, it can be discerned whether a field line from any surface element is open at 2.5 solar radii (source surface) to interplanetary space or returns to the photosphere. In

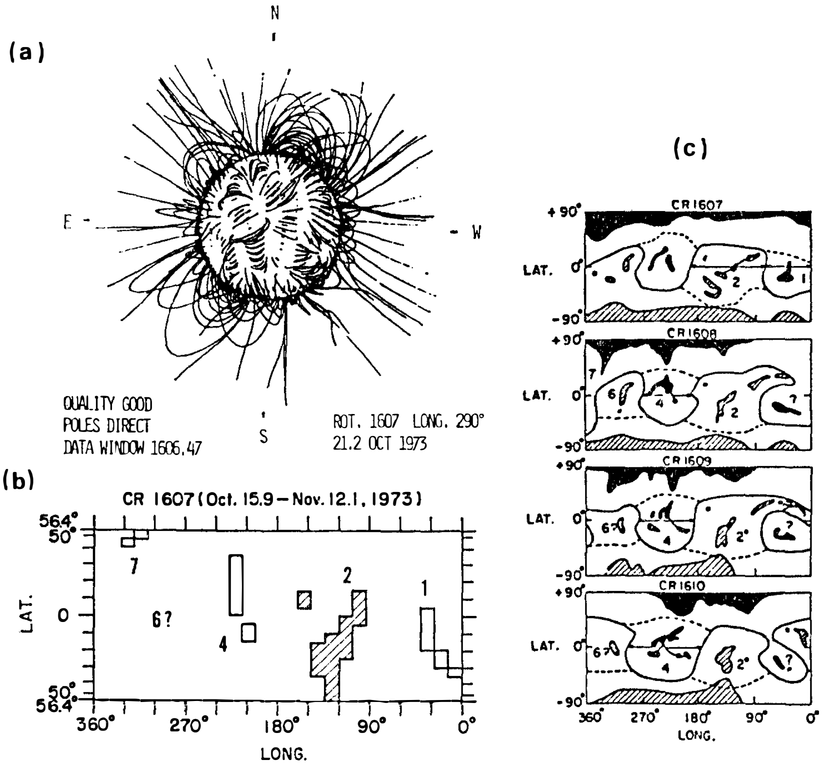

Fig. 1. (a) An example of the general field map provided by the Atlas. This map is drawn for 290° central meridian longitude in Carrington rotation 1607. (b) A synoptic map showing the approximate photospheric footprints of coronal open magnetic field lines for CR 1607. The negative polarity is indicated by the hatching. The attached numbers are the corresponding coronal hole numbers defined for the Skylab period. (c) Maps of the footprints of open magnetic field lines for CR 1607–1610 reproduced from BURLAGA et al. (1978). Solid and hatched areas indicate positive and negative polarities, respectively.

practice, it is very helpful to pursue the appearance of an field line on the successive maps presented at the interval of every 10° solar rotation.

Fig. 1b is a synoptic map for Carrington rotation (CR) 1607 showing the distribution of the photospheric surface elements from which open field lines emerge. Thus, this diagram presents the approximate photospheric footprints of the open magnetic field lines with the resolution of 13.3° in longitude and 5° to 6° in latitude in the latitude range within $\pm 56.4°$. (Note that we had to limit ourselves to this latitude range because of the complexity due to the overlap of field lines in the polar regions.) In this presentation, the time of central meridian passage runs from left to right for convenience of comparison with other data. The magnetic field polarity can be easily determined by pursuing appropriate field lines from a strong field region for which the magnetic polarity is presented on the strong field maps. In the synoptic map of the open field regions in Fig. 1 and subsequent similar diagrams, the negative polarity is indicated by the shading.

We first compare this diagram with a similar map published by BURLAGA *et al.* (1978), which is reproduced in Fig. 1c together with those for the subsequent rotations. In these maps, solid areas show open field regions with positive polarity. It is worthwhile to mention the differences in the precision between the two. First, the spatial resolution is much improved in the magnetic field calculation by BURLAGA *et al.* (1978) by using the photospheric magnetic field measurements with a larger dynamical range from Kitt Peak Observatory (KPO). Secondly, while their synoptic maps are drawn by determining open field lines on the whole source surface at 2.5 solar radii, our maps are based on the identification of the photospheric surface elements whose sample field lines are open. This means that some open field regions of a scale size comparable to the surface element could slip out of our maps. In spite of these limitations, the distributions of open field regions of both maps generally agree with each other including the magnetic polarity. Since there is an obvious correspondence between these open field regions and coronal holes, the cronal hole (CH) numbers accepted for the Skylab period are attached to aid the identification of open structures. The only significant difference between the two maps is the absence of open region associated with CH 6 near 300° longitude in our map. However, this is probably due to the insufficient resolution of our map originating from the mapping method outlined above. In fact, a closer inspection of the original field map shown in Fig. 1a suggests possible existence of open field lines in the equatorial region near the central meridian (290°), because the field lines are of diverging structure as discussed below.

LEVINE (1977) presented synoptic projection plots of open field lines obtained from high-resolution mapping with the KPO magnetograph data for the entire Skylab period. He also made the association between all of the individual open structures and the observed coronal holes or active regions. We compared the Atlas data with Levine's synoptic maps, with the intention of examining the signature

Table 1. Magnetic field structures associated with coronal holes.

Solar rotation	Coronal hole identification							
	CH 1	CH 2	CH 2*	CH 3	CH 4	CH 5	CH 6	CH 7
1601	OPEN	OPEN		DIVR		OPEN		
1602	OPEN	NOSG		OPEN		OPEN		
1603	OPEN	DIVR		DIVR		OPEN	(DIVR)	
1604	DIVR	OPEN		DIVR	(DIVR)	OPEN	(DIVR)	(DIVR)
1605	OPEN	OPEN		(DIVR)	(OPEN)	OPEN	(DIVR)	(OPEN)
1606	DIVR	OPEN			OPEN		(DIVR)	OPEN
1607	OPEN	OPEN			OPEN		DIVR	OPEN
1608	(OPEN)	(DIVR)	OPEN		OPEN		OPEN	OPEN
1609	(DIVR)	(DIVR)	OPEN		OPEN		(DIVR)	NOSG

Note: Three classifications are used; open structure (OPEN), diverging structure suggesting existence of open field lines (DIVR), no signature of open field lines (NOSG).

of coronal holes on the plots of field lines provided in the Atlas. Table 1 shows the resultant identification of the magnetic field structures corresponding to the coronal hole regions for CR 1601–1609.

It is evidently seen that the coronal hole regions are generally identified on the Atlas field line plots as the regions of open or diverging magnetic field structures. Here, the diverging region means a rather large unipolar region with the magnetic field configuration in the surrounding region suggesting that a more detailed plot should reveal some open field lines. In the table, magnetic field structures in parentheses indicate that they are found in rotations before and/or after the period in which coronal holes are seen in the Skylab X-ray photographs. Thus, with the use of the Atlas by NEWKIRK *et al.* (1973), we can pursue the evolution of open magnetic structures and its relation to coronal holes as discussed previously by LEVINE (1977, 1978). It should be noted here that CH 2* separated from CH 2 in CR 1608. In the nine rotation period examined, there are only two cases; CH 2 in CR 1602 and CH 7 in CR 1609, in which no signature of open field lines could be found on the field line plots. The latter of these two cases is probably related to the decay of open structure in this region, which is evident in the map for CR 1610 in Fig. 1c. Because the magnetic field calculation needs data from at least one complete solar rotation, it is plausible that the inconsistent feature was obtained owing to such time variations in the real magnetic structure.

Now that the reliability of the Atlas data has been verified, let us examine the relation of coronal open magnetic structures to the solar wind streams. In Fig. 2, the interplanetary plasma and magnetic field data are compared with the photospheric footprints of open field regions for the period from 26 August to 8 October, 1967. The interplanetary data were taken from the plots of hourly averages in the

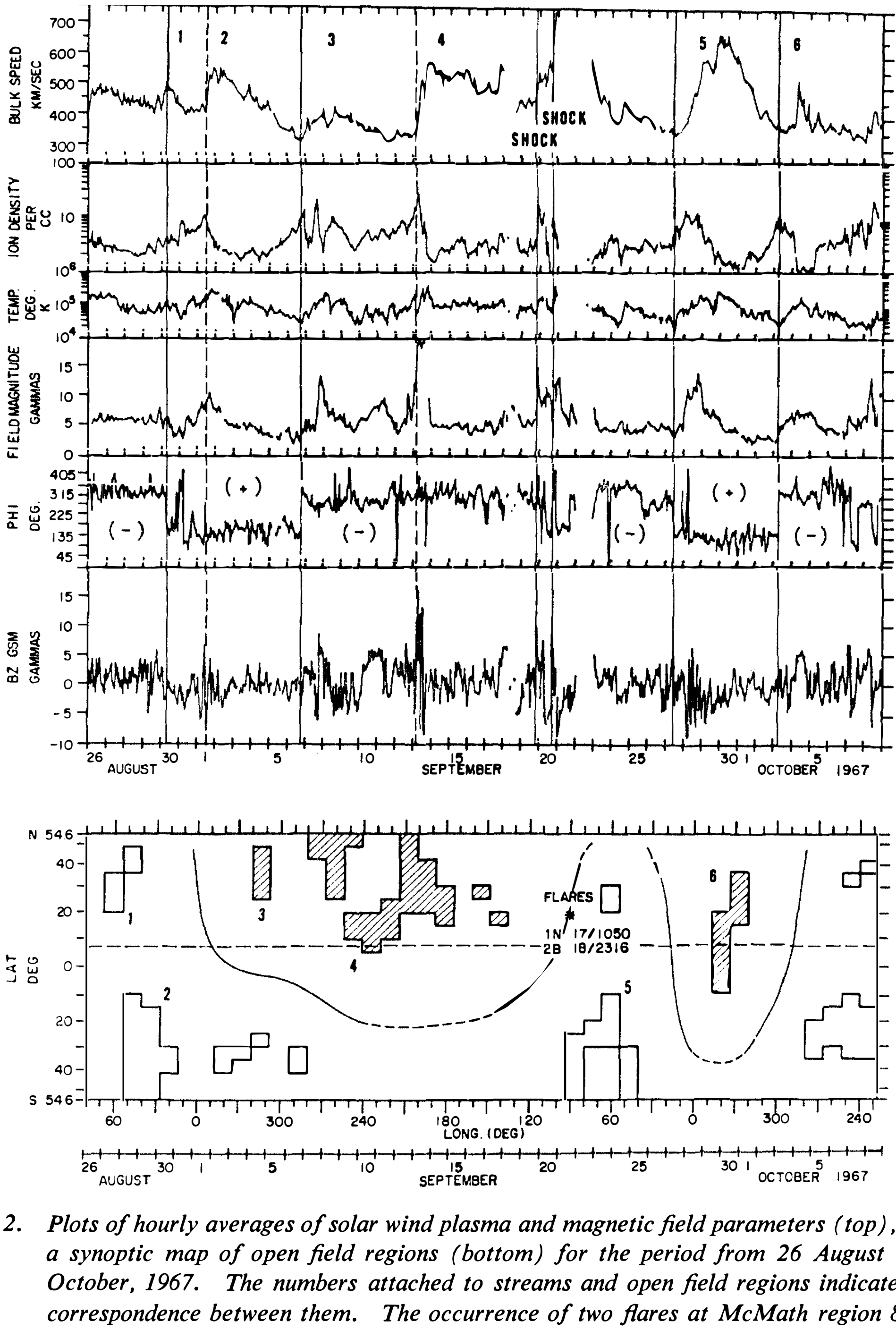

Fig. 2. Plots of hourly averages of solar wind plasma and magnetic field parameters (top), and a synoptic map of open field regions (bottom) for the period from 26 August to 8 October, 1967. The numbers attached to streams and open field regions indicate the correspondence between them. The occurrence of two flares at McMath region 8973 (denoted by the asterisk) and the corresponding shocks are also indicated. In the bottom figure, two lines are drawn to denote the inferred sector boundary on the source surface and the heliographic latitude of the earth.

Interplanetary Medium Data Book compiled by KING (1977). In the map of open field regions, a line is drawn which runs approximately midway between adjacent open regions with opposite magnetic polarities, intended to indicate the approximate sector boundary on the source surface. The heliographic latitude of the earth in this period is also shown by a dashed line.

We can see an obvious correspondence between the streams and the open field regions as shown by the numbering of streams and corresponding open field regions. Each of the streams exhibits the enhancements in the magnetic field intensity and the plasma density in the region where the bulk speed is increasing. This feature is one of the characteristics of corotating streams (BURLAGA, 1975). The magnetic polarity of each stream agrees with the polarity of the coronal magnetic field in the corresponding open field region. The inferred sector boundary on the source surface also seems compatible to the crossings of the sector boundary at 1 AU. However, more detailed data on the magnetic field structure near the source surface are needed to study the compatibility of the sector boundary crossings with the observed speed of each stream.

There occurred two major flares in McMath plage region 8973 located near 90° Carrington longitude as indicated in Fig. 2 (DODSON and HEDEMAN, 1971). The first flare of importance 1N took place at 1050 UT on 17 September, and was associated with a strong type IV burst at decametric band. The second flare is even larger (importance 2B) and occurred at 2316 UT on 18 Septebmer, 1967. This flare was also accompanied by strong type II and type IV radio bursts. Thus, both flares seem to be capable of producing interplanetary shocks (COOK and MCCUE, 1975). Therefore, it is reasonable to ascribe two shock structures at 1959 UT on 19 September and at 1736 UT on 20 September to these two flares. The delay time from the flare to the shock arrival comes to 57 hours for the first event, and to 42 hours for the second event. It is also seen in Fig. 2 that the flare ejecta perturbed the longitude angle of interplanetary magnetic field (IMF) within the sector region of long-lasting negative polarity.

Similar comparison between coronal magnetic structures and interplanetary streams was attempted for the period from July 1967 to May 1968 (CR 1523–1534), because a nearly complete set of interplanetary data is available in this period (KING, 1977). This period is also of interest because it is in the increasing phase of solar activity just before the maximum of solar cycle 20. Unfortunately, the poor quality of the coronal field maps for CR 1526–1531 prevented us to draw any conclusive result from these rotations. (The quality of coronal field maps of the Atlas is classified into three ranks: Good, Fair and Poor.) However, the data from the remaining rotations exhibited a generally good correspondence including magnetic polarities between coronal open magnetic structures and solar wind streams, with occasional perturbations caused by solar flares. It is also worth mentioning that in the period investigated here the open field regions with positive magnetic polarity tend to appear predominantly in the southern hemisphere and those with negative polarity in the northern hemisphere. This tendency is consistent with the finding during the Skylab period that the midlatitude coronal holes in the northern (southern) hemisphere predominantly form in the unipolar cells having the same polarity as the northern (southern) polar cap magnetic field (BOHLIN, 1976). Also note that the polar cap magnetic fields are reversed around the solar maximum phase between the period studied here and the Skylab period.

3. Recurrent Geomagnetic Disturbances and Coronal Open Magnetic Structures

Fig. 3 presents the 27-day recurrence diagrams of geomagnetic C9 index for solar cycles 19 and 20, in which the higher geomagnetic activity is shown by the darker shading. The times of solar maximums and minimums are indicated by the small triangles at the left of the year axis. The exact values of C9 indices are plotted in the left diagram for each solar cycle. The right diagram emphasizes the recurrent tendency in geomagnetic activity, being the plot of the 15-days averages taken for both Bartels rotations and days of rotation. The average value for the i-th day of the r-th rotation $\overline{C9}\,(r, i)$ is defined as follows:

$$\overline{C9}\,(r, i) = \sum_{r,i} C9\,(r, i)/15$$

where the summation is taken for $r=r-2, \ldots, r+2$, and $i=i-1, \ldots, i+1$. At the end of each Bartels rotation of each diagram, data for subsequent 10 days are added to aid easier recognition of recurrence tendency near the end of rotations. This figure reveals a feature that the geomagnetic activity is higher in the first half than in the last half in solar cycle 19 and the converse is true in solar cycle 20, in agreement with the finding by CHERNOSKY (1966). In addition, the strong recurrent tendency is evident in the declining phase of solar activity toward the end of each solar cycle. It is interesting to note that several series of recurrent trends are seen in the period from 1956 to 1961. We selected two intervals, December 1959 to June 1960 and June 1963 to January 1964, for the present study of the relation between coronal open magnetic structures and geomagnetic disturbances. These two intervals were selected from the consideration of both the coverage of coronal data and the apparent predominance of recurrent geomagnetic activity, one in the time of high solar activity and the other in low solar activity.

In Fig. 4, geomagnetic activity is compared with coronal open magnetic structures for the period from December 1959 to June 1960. The first diagram is the plot of C9 indices for Bartels rotations 1728–1741, representing two series of recurrent geomagnetic activity to be discussed below (series A and series B). While the near 28-day recurrence of series A is self-evident, series B and its recurrence time are not so

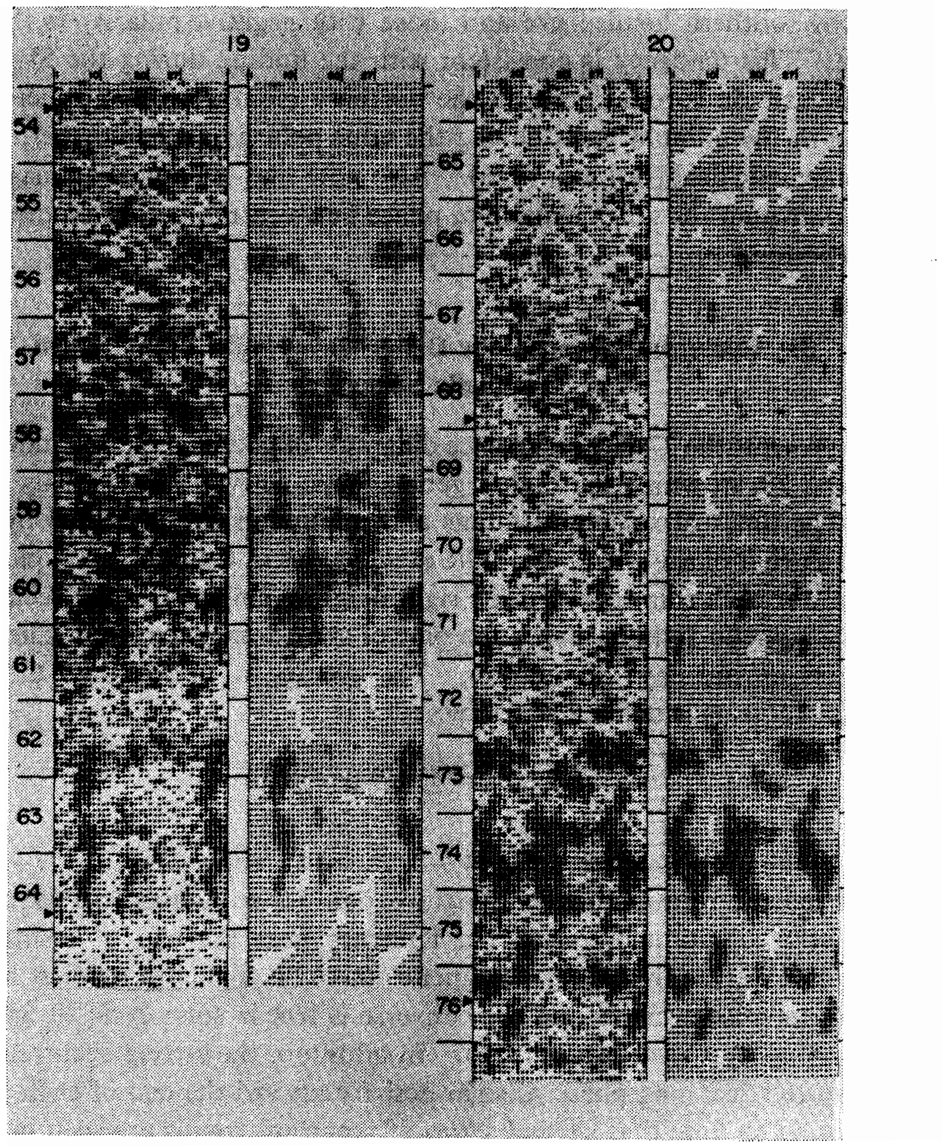

Fig. 3. The 27-day recurrence diagrams of C9 index for solar cycles 19 and 20. The darker shading indicates the higher geomagnetic activity. For each solar cycle, the left diagram is the plot of exact values of C9 indices and the right is the plot of 15-days average values (see text), emphasizing the recurrent activity. At the end of each Bartels rotation, data for subsequent 10 days are added to aid pattern recognition. The times of solar maximums and minimums are indicated by the small triangles.

clear. However, the near 28-day recurrence is identified also for series B by the close examination described below. The remaining diagrams in Fig. 4 show the synoptic maps of the photospheric footprints of coronal open magnetic field lines and the variations in C9 index and in the IMF polarity at 1 AU inferred from ground geomagnetic observations (SVALGAARD, 1975) for the period of CR 1422–1428. The

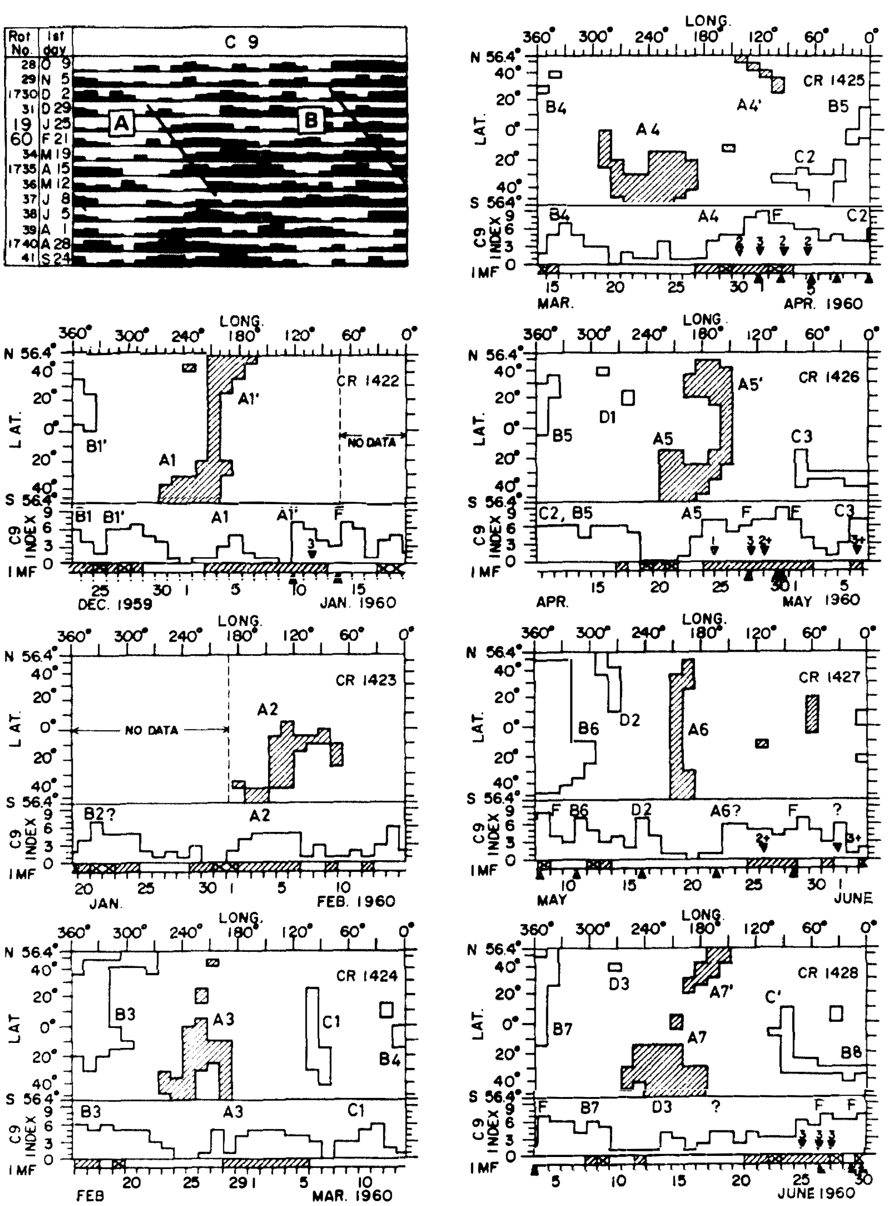

Fig. 4. *Comparison of geomagnetic activity with open magnetic structures of corona and solar flares during the period CR 1422–1428. The first figure shows two marked series of recurrent geomagnetic disturbances. The subsequent diagrams present the maps of open field regions and the variations in C9 index and in the IMF polarity. The hatchings show negative polarity and the crosses indicate uncertain or mixed polarity. The labels attached to geomagnetic disturbances and open field regions show the correspondence between them. Geomagnetic disturbances caused by flares are labeled F. The small triangles underneath the time axis indicate the ssc's, and the corresponding flares are shown by the inverted triangles along with numbers denoting the flare importance.*

ssc's reported in this period are indicated by the small triangles underneath the time axis. The inverted triangles above the line of IMF polarity indicate the occurrence of solar flares which can be taken as causes of the ssc's, the flare importance being indicated by the attached number. Table 2 presents further details of these flares and also their likely relations to the ssc's. Here, the flare data were taken from the list of "major" flares compiled by DODSON and HEDEMAN (1971).

As is evident in Fig. 4, open field structures are seen predominatingly in two longitude regions about 180° apart from each other. One is the region around 180° Carrington longitude with negative magnetic polarity, and the other is the region with positive polarity around 0° longitude. It is also noted that these two regions (henceforth referred to as region A and region B, respectively) cover a rather wide latitude range. The original field maps for this period show that the magnetic field lines over polar regions are mostly closed and form loop structures. These features are very conspicuous and persistent in the period shown here, which is just after the solar maximum phase. Altogether, the Atlas field maps for this period exhibit such a magnetic field configuration as is dominated by a dipole field with its axis tilting nearly 90° from the rotation axis (see also Fig. 5). Correspondingly, the IMF polarity

Table 2. Association of ssc's with solar flares.

Flare characteristics						ssc	Delay
Date Time (UT)	Position	Imp.	McMath plage	Profile abcde	Index	Date Time (UT)	time (h)
1960						1960	
Jan. 11 2040	N22 E02	3	5527	2323-	≥10	Jan. 13 1859	46.4
Mar. 30 1520	N12 E11	2	5615	32333	14	Apr. 1 0307	35.8
Apr. 1 0843	N12 W11	3	5615	333-3	≥12	Apr. 2 2313	38.5
Apr. 3 0542	N11 W36	2	5615	322-0	≥ 7	Apr. 5 1300	55.3
Apr. 5 0215	N12 W63	2	5615	32332	13	Apr. 7 1511	60.9
Apr. 24 2332	N15 E35	1	5642	11030	5	Apr. 27 2020	68.8
Apr. 28 0130	S05 E34	3	5645	33230	11	Apr. 30 0132	48.0
Apr. 29 0107	N14 W21	2+	5642	22232	11	Apr. 30 1213	35.1
May 6 1404	S08 E07	3+	5653	3323-	≥11	May 8 0421	38.3
May 26 0850	N14 W15	2+	5669	223-3	≥10	May 28 2029	59.7
June 1 0823	N29 E46	3+	5680	333-3	≥12	June 4 0248	66.4
June 25 1136	N21 E06	3	5713	2323-	≥10	June 27 0145	38.2
June 26 2358	S08 E34	3	5719	23133	12	June 29 1939	67.7
June 27 2140	N22 W27	3	5713	23232	12	June 30 1720	68.7

Note: The flare profile is defined by the intensity of five components; sudden ionospheric disturbance, $H\alpha$ importance, magnitude of $\lambda = 10$ cm radio flux, dynamic spectrum of radio burst, magnitude of radio flux near 200 MHz. The index is defined as the sum of five profile components. For more details see DODSOM and HEDEMAN (1971).

in this period displays a pattern predominated by the two-sector structure (see also SVALGAARD and WILCOX, 1975). However, it should be noted that the high-resolution harmonic analysis of the KPO magnetograph data yields different results about the dominant multipole components of coronal magnetic field from those by the analysis of the Mt. Wilson data (ALTSCHULER *et al.*, 1977). This study pointed out a possibility that a dipole component is too much emphasized in the Atlas field maps.

In Fig. 4, geomagnetic disturbances and open field regions are labeled to indicate their possible associations. A question mark is attached to the labeling if the association is not very clear. In addition, geomagnetic disturbances probably caused by flares are indicated by labeling F, and their associations with flares are shown in Table 2. There is an obvious correspondence between the geomagnetic disturbances and the coronal open magnetic structures. Generally, geomagnetic disturbances occur several days after central meridian passage of the corresponding coronal open field regions. The IMF polarity during each disturbance coincides with the polarity of the corresponding open field region. This correspondence strongly suggests that the open field regions identified here are the sources of fast solar wind streams which caused the observed geomagnetic disturbances. We can see an excellent association between the recurrent disturbances of series A and the region of open field lines around 180° longitude (region A), with only one exception in CR 1428. Although many major flares occurred in the period studied here, most of them do not seem to have perturbed the streams from region A. The recurrent series B is somewhat confused in comparison with series A by effects of disturbances associated with flares and other open field regions. Namely, the starting times of disturbances B5 and B7 are not clear because of continuance of preceding disturbances. Nevertheless, effects of streams from region B are evident, because such long-lasting geomagnetic disturbances could not be expected without them. It is also seen that some of the disturbances in series B exhibit the IMF polarity inconsistent with the magnetic po-

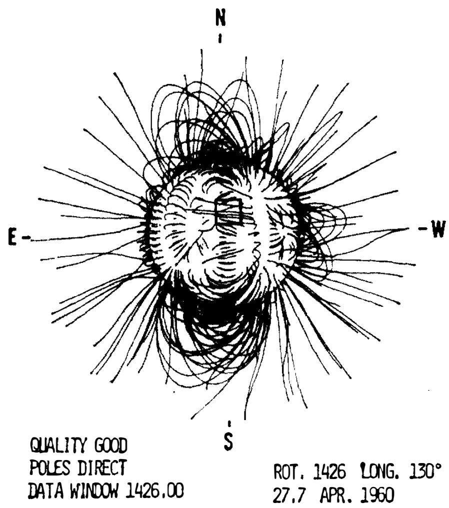

Fig. 5. An example of the coronal field map for CR 1426. The central meridian longitude is 130°. The square on the map shows the position of McMath region 5642.

larity of region B. This inconsistency may be ascribed to the possible bias in the inferred IMF polarity toward assigning negative polarity on geomagnetically disturbed days that was first pointed out by RUSSELL *et al.* (1975).

The flare activity was particularly high in CR 1425 and CR 1426. The sequential flares in CR 1425 possibly responsible for the four ssc's took place in McMath plage region 5615. Out of the three flares followed by three ssc's nearly in the same rotation phase in CR 1426, two flares occurred in this same region (numbered 5642). During the next rotation, the same region now numbered 5669 again produced a 2B flare which also caused an ssc. Thus, the repeated flare activity in one active region explains the seemingly recurrent severe disturbances following the disturbances in series A in the 27-day recurrence diagram. It is interesting to note the position of this active region relative to the open field regions. Fig. 5 presents a coronal field map from the Atlas for 130° CML in CR 1426, in which the position of McMath region 5642 is indicated by the square. This region lies in the closed field structure roughly midway between open field region, region A and regions B/C. Such disposition is favorable for separate detection of the effects of streams from open field regions and those of flare-produced shocks. BURLAGA and SCUDDER (1975) showed a possibility that flare-produced shocks may disappear when overtaking a corotating stream as a result of interaction with it. In this connection, it would be of interest to survey the occurrence of flares more completely and examine possible differences in their effects depending on their disposition relative to sources of corotating streams. Such a study will be made in the future.

Fig. 6 presents the plot of C9 indices for Bartels rotation 1775 to 1788 and the maps of open field regions during the period from June 1963 to January 1964, along with the corresponding C9 index and IMF polarity variations in the same format as Fig. 4. Two marked series of recurrent activity are indicated in the first diagram by the solid lines. The lines are drawn only for the interval in which the associations with open field regions were identified. Series A apparently continues from earlier rotations (see also Fig. 3), but unfortunately the gap of coronal data from CR 1462 to CR 1467 prevents similar comparison. (Also note the data gap from 3 September to 4 October or from 180° longitude in CR 1471 to 120° in CR 1472.) The dashed lines indicate the existence of four series of recurrent disturbances in the subsequent several rotations. The third series is apparently the continuation of series B. We call them series A′, B, C, D as shown in the figure. These four recurrent series will also be discussed briefly below. It is worthwhile to note here again that the open field regions with positive magnetic polarity tend to appear predominantly in the southern hemisphere and those with negative polarity in the northern hemisphere. This tendency is consistent with the relation between the magnetic polarity of midlatitude coronal holes and the polarity of polar cap magnetic fields found during the Skylab period (BOHLIN, 1976), as previously discussed.

In Fig. 6, one can readily see the correspondence between geomagnetic disturb-

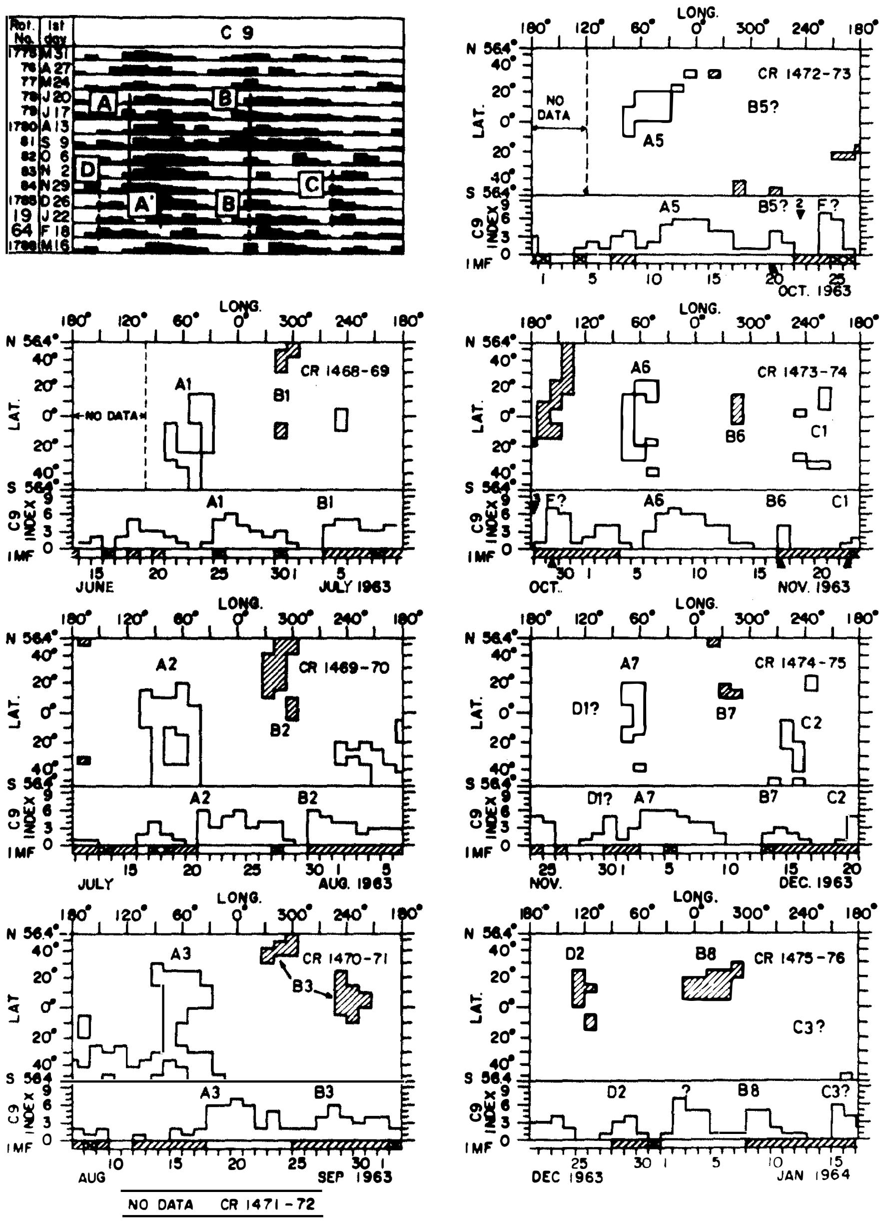

Fig. 6. Same as Fig. 4 except for CR 1468–1476.

ances and coronal open field regions as shown again by the labeling. The maps of open field regions include three possible open regions (B5, D1, and C3 with question marks), in which diverging magnetic structures were identified in the original Atlas plots of field lines. The recurrent geomagnetic disturbances of series A and series B are well associated with the open field region with positive magnetic polarity around 60° longitude (region A) and the negative open field region around 300° (region B), respectively. In these associations, the IMF polarity generally agrees with the polarity of coronal magnetic field. We can see additional recurrent series; series C and series D corresponding to the positive open regions around 240° longitude and the negative regions around 120°, respectively. Though the IMF polarity is inconsistent with the polarity of the corresponding open regions for disturbance C3 and some fractions of C1 and C2, the IMF polarity in the period corresponding to series C is dominated by the positive polarity as a whole. Therefore, this fractional inconsistency may be ascribed again to the inaccuracy of the inferred IMF polarity.

Another region of open field lines is seen around 150° longitude in CR 1473, very close to the longitude of region D. This region seems to be responsible for the negative IMF polarity from 28 October and also some disturbances in this negative sector. However, we did not take the disturbance on 2 and 3 November as the beginning of series D, because a closer inspection of original field line plots suggests that region D developed in a region different from the negative open region in CR 1473. Recurrent series A′ seems to have started with a disturbance which occurred on 2 January, 1964 (attached with a question mark). However, no evidence could be found in the Atlas data in CR 1475 for existence of open field lines to be associated with this disturbance. It seems likely to draw an easy conclusion from the 27-day recurrence diagrams such as Fig. 3 that there was one long-lived series of recurrent disturbances from the latter half of 1962 toward the end of 1964 which had been caused by one identical stream source. However, the present examination of coronal magnetic fields throws doubt on such interpretation. Although we did not further examine the relation between series A and A′, emphasis is laid on the importance of pursuing evolutionary changes in coronal magnetic structures for better understanding of evolution of recurrent geomagnetic disturbances.

Among those recurrent series discussed above, the evolution of series B is particularly interesting. It is evident in Fig. 6 that the degree of geomagnetic activity in series B is correlated with the evolution of the corresponding open field region. Namely, weak disturbances are seen during the periods when the area of region B is relatively small. This correlation is consistent with the finding that the maximum speeds of corotating streams are well correlated with the area of the corresponding coronal holes (NOLTE *et al.*, 1976). The evolution of region B is of interest also in relation to the annual variation of geomagnetic activity. BURCH (1973) and RUSSELL and MCPHERRON (1973) showed that the geomagnetic effect of streams with negative IMF polarity is strongest in the northern hemisphere spring and the effect of positive streams is strongest in the fall. The present study shows that the observed change in geomagnetic activity in the recurrent series B is the result of not only the annual variation of the polarity effect but also the evolution of the stream associated with region B.

4. Summary

A study has been made on the relations between geomagnetic disturbances, interplanetary streams and magnetic fields, coronal holes, and coronal magnetic field structures with the use of the Atlas of Magnetic Fields in the Solar Corona published by NEWKIRK *et al.* (1973) for four selected periods. Some of the principal results of the study from each period are summarized below.

(1) The examination of the Atlas field maps during Carrington rotations 1601 to 1609 (May 1973 to January 1974) showed that the coronal hole regions generally correspond to the regions of open or diverging magnetic structures of corona. It was also shown that the lifetimes of open field regions are generally longer than those of coronal holes. These results are consistent with the findings in similar studies with coronal magnetic field data of higher resolution (LEVINE, 1977, 1978; BURLAGA *et al.*, 1978), and verify the reliability of the Atlas data.

(2) An excellent correspondence was found between coronal open field structures and interplanetary streams during the period from 26 August to 8 October 1967. Similar comparison between the Atlas field maps and the interplanetary plasma and magnetic field observations revealed a generally reasonable correspondence between coronal open magnetic structures and solar wind streams for the most part of the period from July 1967 to May 1968, with occasional perturbations caused by solar flares. It is important to note here that this period is in the increasing phase of solar activity just before the maximum phase of solar cycle 20.

(3) Comparison between geomagnetic disturbances and coronal magnetic structures for the period from December 1959 to June 1960 revealed the existence of two long series of recurrent geomagnetic disturbances. Two long-lived open field regions were identified as the sources of corotating streams which caused these two recurrent series. The recurrent times of these two series were found to be about 28 days, which are not necessarily evident in the 27-day recurrence diagram without identification of the corresponding open field region.

(4) A clear correspondence was found between two long series of recurrent geomagnetic disturbances and two persistent regions of open magnetic structures also during the period from June 1963 to January 1964. In one of these two series, a good correlation was found between the geomagnetic activity and the evolution of the corresponding open field region. It was also pointed out that the identification of series of recurrent disturbances based solely on the 27-day recurrence diagram may yield misleading results in some cases.

In conclusion, the present study emphasizes the importance and usefulness of pursuing evolutionary changes in coronal magnetic structures to the study of recurrent geomagnetic disturbances in connection with the identification of sources of corotating streams. It can be said that identifying stream sources in the solar corona is the first step to be done in order to study the dynamics of streams in interplanetary space.

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References

ALTSCHULER, M. D., LEVINE, R. H., STIX, M. and HARVEY, J. (1977): High resolution mapping of the magnetic field of the solar corona. Solar Phys., **51**, 345–375.

BELL, B. and NOCI, G. (1976): Intensity of Fe XV emission line corona, the level of geomagnetic activity, and the velocity of the solar wind. J. Geophys. Res., **81**, 4508–4516.

BOHLIN, J. D. (1976): The physical properties of coronal holes. Proceedings of the International Symposium on Solar Terrestrial Physics, Vol. 1, ed. by D. J. WILLIAMS. Washington, D. C., Am. Geophys. Union, 114–128.

BURCH, J. L. (1973): Effects of interplanetary sector structure on auroral zone and polar cap magnetic activity. J. Geophys. Res., **78**, 1047–1057.

BURLAGA, L. F. (1975): Interplanetary streams and their interaction with the earth. Space Sci. Rev., **17**, 327–352.

BURLAGA, L. F. and SCUDDER, J. D. (1975): Motion of shocks through interplanetary streams. J. Geophys. Res., **80**, 4004–4010.

BURLAGA, L. F., BEHANNON, K. W., HANSEN, S. F., PNEUMAN, G. W. and FELDMAN, W. C. (1978): Sources of magnetic fields in recurrent interplanetary streams. J. Geophys. Res., **83**, 4177–4185.

CHERNOSKY, E. J. (1966): Double sunspot-cycle variation in terrestrial magnetic activity, 1884–1963. J. Geophys. Res., **71**, 965–974.

COOK, F. E. and MCCUE, C. G. (1975): Solar terrestrial relations and short-term ionosphere forecasting. Radio Electron. Eng., **45**, 11–30.

DODSON, H. W. and HEDEMAN, E. R. (1971): An experimental, comprehensive flare index and its derivation for "major" flares, 1955–1969. World Data Center A, Upper Atmosphere Geophysics, Report UAG-**14**, 25 p.

HANSEN, R. T., HANSEN, S. F. and SAWYER, C. (1976): Long-lived coronal structures and recurrent geomagnetic patterns in 1974. Planet. Space Sci., **24**, 381–388.

KING, J. H. (1977): Interplanetary Medium Data Book. Rep. NSSDC 77-04, Greenbelt, NASA Goddard Space Flight Center.

LEVINE, R. H. (1977): Evolution of open magnetic structures on the sun: The Skylab period. Astrophys. J., **218**, 291–305.

LEVINE, R. H. (1978): The relation of open magnetic structures to solar wind flow. J. Geophys. Res., **83**, 4193–4199.

LEVINE, R. H., ALTSCHULER, M. D., HARVEY, J. W. and JACKSON, B. V. (1977): Open magnetic structures on the sun. Astrophys. J., **215**, 636–651.

MARUBASHI, K. and ISHII, T. (1980): Geomagnetic storms and related solar phenomena. Nankyoku Shiryô (Antarct. Rec.), **68**, 47–62.

NEUPERT, W. M. and PIZZO, V. (1974): Solar coronal holes as sources of recurrent geomagnetic disturbances. J. Geophys. Res., **79**, 3701–3709.

NEWKIRK, G., JR., TROTTER, D. E., ALTSCHULER, M. D. and HOWARD, R. (1973): A Microfilm Atlas of Magnetic Fields in the Solar Corona, NCAR-TN/STR-85.

NOLTE, J. T., KRIEGER, A. S., TIMOTHY, A. E., GOLD, R. E., ROELOF, E. C., VAIANA, G., LAZARUS, A. J., SULLIVAN, J. D. and MCINTOSH, P. S. (1976): Coronal holes as sources of solar wind. Solar Phys., **46**, 303–322.

RUSSELL, C. T. and MCPHERRON, R. L. (1973): Semiannual variation of geomagnetic activity. J. Geophys. Res., **78**, 92–108.

RUSSELL, C. T., BURTON, R. K. and MCPHERRON, R. L. (1975): Some properties of the Svalgaard A/C index. J. Geophys. Res., **80**, 1349–1351.

SHEELEY, N. R., JR., HARVEY, J. W. and FELDMAN, W. C. (1976): Coronal holes, solar wind streams, and recurrent geomagnetic disturbances: 1973–1976. Solar Phys., **49**, 271–278.

SHEELEY, N. R., JR., ASBRIDGE, J. R., BAME, S. J. and HARVEY, J. W. (1977): A pictorial comparison of interplanetary magnetic field polarity, solar wind speed, and geomagnetic disturbance index during the sunspot cycle. Solar Phys., **52**, 485–495.

SVALGAARD, L. (1975): An atlas of interplanetary sector structure, 1957–1974. Inst. Plasma Res., Standford Univ., Rep. **648**, 84 p.

SVALGAARD, L. and WILCOX, J. M. (1975): Long term evolution of solar sector structure. Solar Phys., **41**, 461–475.

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